STUDIES OF ELECTROMAGNETIC SOUND GENERATION FOR NDE*

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INTRODUCTION

This paper will first provide a brief review of the physics of the electromagnetic generation process in metals and semiconductors and secondly, a discussion of the goals of our present project involving the application of this technique to NDE.

The foremost advantage of electromagnetic generation of ultrasonic waves is the contactless nature of the process. To illustrate the importance of this, standard methods of generating ultrasonic waves must first be described. In the laboratory, the preferred technique is the use of a bonding agent such as grease or glue to couple the piezoelectric transducer to the specimen. Such bonds are usually rigid and produce negligible attenuation and spurious reflections in the bond layer. A disadvantage of such a technique is that the bond must be made carefully and there is no scanning capability.

For NDE work, where tests must be made in a relatively short time, such a bond is frequently impractical. One standard technique for NDE is the immersion of the specimen in a liquid bath (usually water) which provides the medium to couple the ultrasonic waves produced by the transducer into the specimen. Since liquids will not transmit transverse sound waves, only compressional waves are generated by the transducer.

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Transverse bulk waves or surface waves must be produced by mode conversion at the specimen-liquid interface.

Several problems arise from the use of such immersion techniques. The additional interfaces present can produce spurious information which must be eliminated. Also, the bath itself can cause corrosion problems which must be avoided by shielding the specimen from the bath. These problems do not arise when a contactless generation method is used.

ELECTROMAGNETIC GENERATION OF ULTRASOUND

In 1967 it was accidentally discovered by two groups, Gantmaker and Dolgopolov[1] in the Soviet Union and Larsen and Saermark[2] in Denmark, that acoustic waves could be excited in metals at helium temperatures by electromagnetic waves. Shortly thereafter, it was found that this electromagnetic generation was possible at any temperature in metals. The basic experimental arrangement is shown in Fig. 1. The electronics are basically the same as for a conventional ultrasonic system. The major difference is that the piezoelectric transducers are replaced by RF coils and a static magnetic field is now required for sound generation. The relative orientation of the static magnetic field and the RF magnetic field determines the polarization of the sound wave generated. This is another of the advantages of the direct generation process, both compressional and transverse waves can be excited by the same coil.

The physical basis of electromagnetic generation can be described using simple classical arguments[3]. Let the x and y axes be in the plane of the specimen face and the z axis be perpendicular to that face as shown in Fig. 2. The R. F. magnetic field, B_x, is taken to be in the x direction. This field produces eddy currents J_y in the specimen in the y direction. Both B_x and J_y are maximum at the metal surface and decrease as $\exp[-(1+i)z/\delta]$ inside the specimen. Here δ is the classical skin depth and is given by

$$\delta = c(2\pi\sigma\mu\omega)^{-1/2} \text{ cm} \quad , \qquad (1)$$

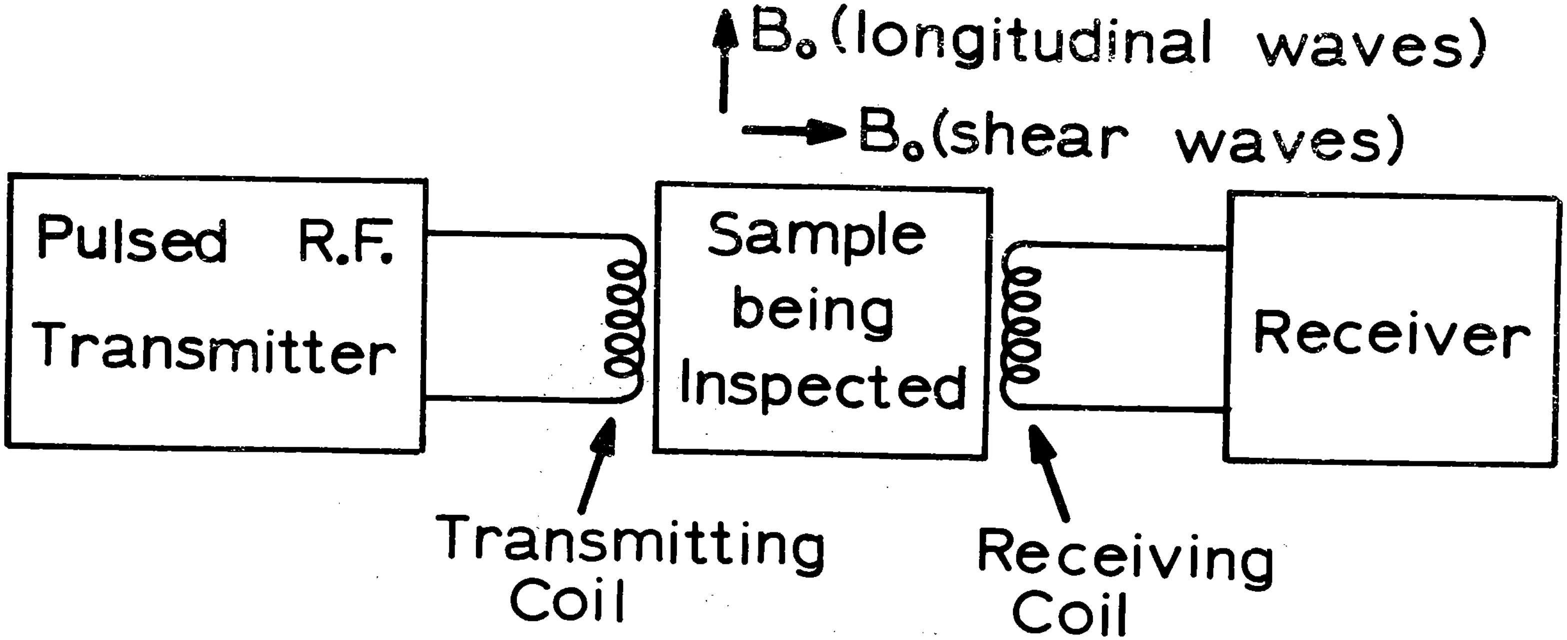

Fig. 1. Block diagram of an experimental set-up for electromagnetic generation of ultrasound.

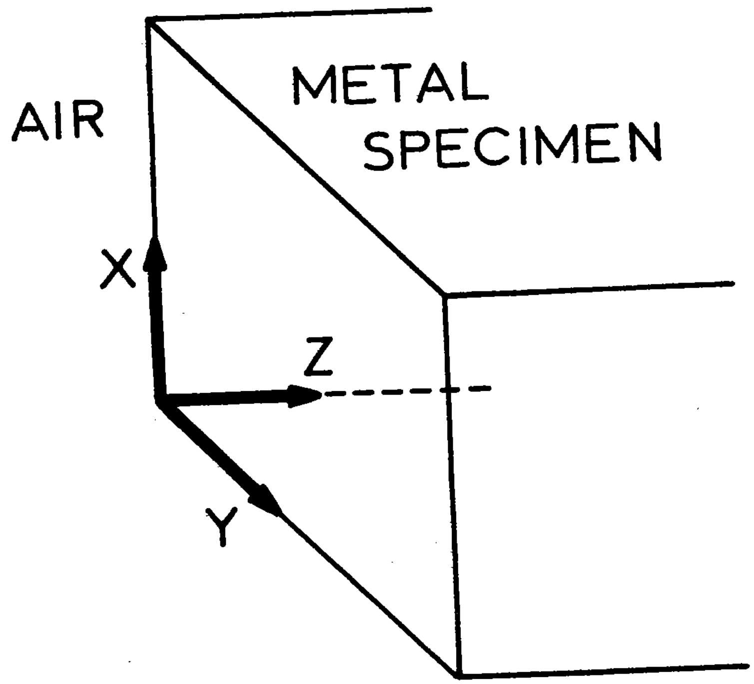

Fig. 2. Coordinate system used in the theoretical description of electromagnetic generation.

where c is the speed of light, σ is the conductivity, μ is the permeability and ω is the frequency.

When a static magnetic field, B_0, is applied, a Lorentz force given by

$$\vec{F} = [\vec{J}_y \times \vec{B}_0] / n_0 c \qquad \text{dynes} \tag{2}$$

acts on the electronic eddy currents. Here n_0 is the number of electrons per unit volume. In the absence of the static field, the electronic and ionic eddy currents act in opposite directions and cancel each other. The electrons transfer their excess momentum to the ions through collisions and the incident electromagnetic energy is dissipated as Joule heat. With the static field, this current balance is upset. For B_0 in the x direction, the Lorentz force is along z or longitudinal. This results in a variation in the electron charge density along z. An internal electric field must be set up along z by the ions to maintain the charge neutrality locally. This field provides the driving force for compressional waves.

If B_0 is in the z direction, the Lorentz force acts in the x direction. Since the electronic and ionic eddy currents are in opposite directions, the Lorentz forces on each are in the same direction and produce a coherent driving force in the x direction.

An equation of motion can be written for a sound wave of amplitude ξ as

$$\frac{\partial^2 \xi}{\partial t^2} - s^2 \frac{\partial^2 \xi}{\partial z^2} = |\vec{J} \times \vec{B}_0| \rho c \quad , \tag{3}$$

where ρ is the density and s is the speed of sound. For the case where $\delta << \lambda$ (λ is the wavelength of the sound wave) and $z >> \delta$, the amplitude of the generated wave is given by

$$|\xi| = \frac{B_x B_0}{4\pi\rho s\omega(1+{}^2)} \tag{4}$$

where $\beta = q^2\delta^2 \quad (q = \frac{2\pi}{\lambda})$.

When the double conversion of electromagnetic energy to ultrasonic energy (transmission and reception) is considered, it is found that the conversion efficiency is proportional to B_0^2. For aluminum at room temperature the efficiency for compressional waves at 10 MHz is $5.7 \times 10^{-13} B_0^2$. At a field of 4 kG, the efficiency is about 30 dB less than for piezoelectric transducers. Thus, if this technique is to be useful for NDE, it is desirable to use larger magnetic fields and high power RF transmitters. It is also necessary to choose the best coil design in order to obtain close to the theoretical efficiency.

Figure 3 shows three possible coil geometries. They are the spiral or pancake, the solenoidal and the flat grid. The spiral geometry was found to be the most efficient at generating sound waves. It has several disadvantages, however. The most serious is the difficulty in obtaining a pure compressional or shear mode. This difficulty arises from the fact that the fringing RF fields of the coil generate the sound waves. Only B_x is necessary for the generation of pure modes, but the circular shape of the coil produces fringing fields which radiate out from the center. Since B_x changes direction at the center of the coil, the generated sound wave is minimum there and there are two maxima near the outer edges. For some applications this can lead to unwanted interference.

The solenoidal design produces fringing fields which are more nearly linearly polarized and, thus, more pure sound wave modes. It has the disadvantage that the fringing fields are weaker and the conversion efficiency is smaller by several dB than for the spiral design.

The flat grid design shown in Fig. 3 represents an attempt to obtain the best features of the spiral and the solenoidal designs in one coil. Only one side of the spiral is used and this side is wound so that the wires are straight and parallel, producing linearly polarized RF fringing fields. It should be noted that this design works best when those segments which would produce unwanted RF fringing fields are screened from the specimen with a thin conducting sheet. Using such screening, the efficiency is comparable to the spiral design.

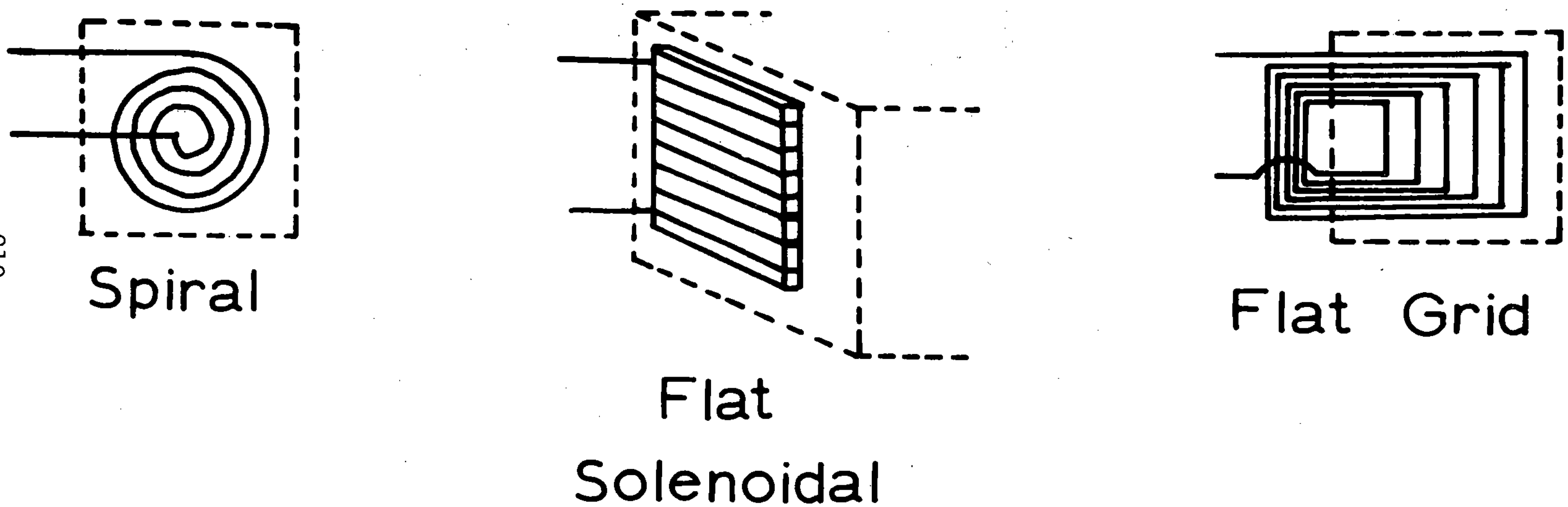

Fig. 3. Typical coil designs used for electromagnetic generation.

It should also be possible to generate waves at angles other than perpendicular to the surface by introducing delay elements between individual wires in the coil. Such generation has been reported in the Soviet Union[4]. This might allow the study of less accessible parts, such as fastener holes.

Surface or Rayleigh waves may also be generated using these techniques. For such generation a meander or serpentine coil is used. Such a coil consists of a grid of parallel wires which have current flowing in opposite directions in adjacent wires.

PRESENT WORK

In addition to the determination of the optimum coil design for each application, a major goal of our present project is the elimination of the need for a bulky electromagnet or permanent magnet. This will be done by generating a pulsed magnetic field in a second coil located near the RF generation coil. A high current video pulse of $\sim 100\ \mu$ will provide the 'static' magnetic field needed for the generation and detection of one or more acoustic echoes.

A second area for investigation is the determination of the depth below the surface of the specimen where the generation actually occurs. Such information is necessary if flaws are to be located with good precision. Much work has already been done in this area and we will perform such studies in materials which have not been studied to date.

The final part of our project is the investigation of the feasibility of using high resolution sound velocity measurements for NDE. Since high resolution velocity measurement systems normally use phase sensitive detection, small changes in the bond would produce large apparent changes in the velocity. With electromagnetic generation these bond errors are eliminated and only changes in the specimen--such as regions with large strains or fatigue--would produce velocity changes. It may also be possible to detect composition variations in the specimen using this technique.

CONCLUSIONS

Electromagnetic generation of sound is a technique which should allow faster and more complete ultrasonic inspection of metals. Since compressional, transverse and surface waves can all be generated using this technique, the means are now available to characterize more completely the types of flaws which are found during the inspection than was possible using standard techniques. In addition, it is the only technique which can be used at high temperatures for such application as quality control of hot alloys just after solidification.

References

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DISCUSSIONS

DR. WILLIAM SCOTT (Naval Air Development Center): I am not sure I completely understand how the force is exerted on the metal. Do the conduction electrons have a Lorentz force exerted on them?

DR. MORAN: Yes.

DR. SCOTT: Does that mean that the efficiency of the sound generation is somehow related to the Hall coefficient of the material?

DR. MORAN: I believe Prof. Maxfield has looked into that aspect.

PROF. BRUCE MAXFIELD (Cornell University): It is directly related to the Hall coefficient.

DR. SCOTT: If you had a material with zero Hall coefficient, then you could generate no sound, is that right?

PROF. MAXFIELD: Insofar as the carriers are immobile, you will not be able to generate any sound that way. The thing is, at high magnetic fields, the compensated metals have no Hall coefficient, but in the type of work being done here at room temperature, you are not in the high field limit. So, even though you are working with a compensated metal such as lead, you have a finite Hall coefficient. There is a finite carrier density present.

DR. SCOTT: Then the phase of the generated sound wave would also change with the sign of the Hall coefficient?

PROF. MAXFIELD: The phase of both the current density and the generated sound wave will change with the sign.

DR. SCOTT: Thank you.

DR. OTTO GERICKE (U. S. Army Materials & Mechanics Research Center): How does the magnetic permeability of the material enter into the efficiency equation?

DR. MORAN: The skin depth will vary with the permeability and the efficiency varies with respect to the skin depth.

DR. MEL LINZER (National Bureau of Standards): You mentioned looking at fasteners. To use this technique, you need access to two sides of the component. How are you going to look at fasteners?

DR. MORAN: A horseshoe type permanent magnet can be used to produce a field either perpendicular or parallel to the surface. Alternatively, a solenoidal electromagnet would produce a field perpendicular to the surface. I would think that the major problem with fasteners would be to get a good reflection back to the top surface.

PROF. MAXFIELD: I would like to make a comment on what you mentioned about generating acoustic waves propagating at an angle to the surface.

DR. MORAN: The Russians say that it is possible.

PROF. MAXFIELD: Yes, we have tried that and have found that it is difficult to keep the amplitude in each of the individual elements constant, while having the phase of one shifted with respect to the other by an equal amount as you go down the line. I would appreciate hearing comments from anyone on how this can be done.